Filters

Filters are used in astronomy for two main purposes, to either lower the overall intensity of the light or to restrict the wavelength range of the light that is being measured. When the eye was the only astronomical detector, filters were scarcely used, but astronomy has always adopted the new technologies of the day, be it photography, photomultiplier tubes, image tubes, CCDs or IR arrays. As the new detectors invariably have a wider wavelength response and/or improved sensitivity than previous detectors, filters became very important in order to match previously used bandpasses and to sample the flux of astronomical sources at different wavelengths thus providing some astrophysical information on the source's temperature and other properties. Some filters work by selective absorption and transmittance: these are the colored glass filters. Others work by selective reflection and transmittance: these are usually referred to as interference filters.

An interference filter comprises a multilayer of thin films that selectively transmits or reflects light of particular wavelengths. They fall into two broad types, bandpass filters (usually narrow bands) and edge filters, that transmit above or below a certain wavelength; dichroic beamsplitters are edge filters. The Fabry-Perot tunable filter is a unique interference filter that can be used to spectacular effect on emission-line objects. Finally, there are filters used for measuring polarized light and studying astronomical magnetic phenomena.

Colored glass filters

The first filters used in astronomy were colored glass (Schott or Corning) or colored gelatin (Kodak). These were used with photographic emulsions to define B, V, R, and I bands. Colored glasses had been made for thousand of years for expensive glass vessels and ornaments. Nowadays, colored glasses are produced in one of two ways, either by ionic coloration or by absorption and scattering from a suspension of colloidal particles that are produced in the glass and controlled in size by heat treatment after an essentially colorless glass is made. In Fig. 1 are shown some sample transmittance curves of these glass filters.

The ionic glasses are made by dissolving particular salts (such as cobalt or nickel oxide) in glass. The ionic coloration of the UG (violet) and BG (blue) series of glasses produces a spectral transmittance curve resembling a bell-curve of half-width between 100 and 200 nm but most of these glasses also transmit red light beyond 700 nm as well, thus the violet glasses appear purple to the eye.

The second type of colored filter glass are a series of sharp edge (or short wave cut-off) filters, the WG, GG (sulphur and cadmium sulfide), OG (cadmium selenide) and RG (gold) series which absorb light blueward of a quite sharply defined wavelength. The filters are made with their short wave cutoffs ranging from 400 to 800 nm in steps of 20 nm. To the eye, the WG glasses are essentially colorless, the GG series go from colorless through light yellow to dark yellow, the OG are orange-red and the RG series are rose to ruby in color.

Schott also make two special (nearly) colorless glasses (BG39/40 and the KG series) that can be used as long wave cutoff filters; however, these glasses have long wave cutoffs that fall more slowly (over about 250 nm) than the short wave cutoffs rise (over about 50 nm) thus producing an asymmetrical spectral transmittance curve when used together to define a bandpass. Where a steeper cutoff is desirable, it is necessary to use an edge interference coating (see below) in combination with a Schott short wave cutoff filter. An important use for the BG39/40 and S8612 glasses is also as a "red-leak" blocker, absorbing light beyond 700 nm where most of the Schott blue and violet glasses transmit. Polished copper sulfate crystals or a copper sulfate solution have also been used in astronomy as a UV transmitting blue filter to block red leaks, but the improved UV transmission of S8612 glass, although not as high as that of copper sulfate, has enabled it to replace copper sulfate for most imaging applications.

Combination filters and bandpasses

The ionic colored glasses define broad bell-shaped bandpasses in the violet, blue or green regions; however, the choice is restricted. Better definition has traditionally been obtained by combining one of those filters with one of the long pass glass filters, or by using a long pass glass filter and the red sensitivity cutoff of the detector, for instance the particular sensitization of a photographic emulsion (O, G, D, E, J, F, N) or the fall-off in the sensitivity of a photocathode (S5, S11, S20, GaAs). But with the use of wide wavelength response CCD detectors and the restriction of photographic emulsions to the broad band Tek Pan film, it is now necessary to have filter defined bandpasses. This is also true in the IR and the UV where in the past, the atmospheric windows were often partly used to define the edges of the bandpass resulting in the bandpass differing between seasons and with observing altitude. The standard U, B, V & R bandpasses can be defined using only glass filters but better R and I bandpasses can be made using interference edge filters for the red cutoffs. The bandpass filters for the Sloan Digital Survey have been defined in this fashion, the short wave cutoff coming from the Schott color filter and the long wave cutoff from an interference edge filter. It is necessary to use BG39 with other BG glasses and S8612 with UG glasses to eliminate the red leak of those glasses.

Combination glass filters have been used successfully with CCD systems to match the standard UBVRI system (see Magnitude Scales and Standard Systems). The thicknesses of the glasses can be adjusted to tune the passband for better results with detectors having different wavelength responses.

Practical consideration

From a practical viewpoint, many of the BG and all the UG glasses are difficult to use. They are hard to polish, tarnish in air easily and the high concentration of ions in the available glasses often means that they are brittle and the required blue or violet color is produced with only a thin piece (1mm or less) of the glass. This is unfortunate, as it means that it is difficult to produce good optical quality glass sandwiches in a large enough size to cover the focal plane of the large Schmidt telescopes where it is desirable to have such a blue and ultraviolet filter for use with the new Tek Pan film. However, up to 25 cm square filters suitable for CCD arrays can readily be made. Large glass pieces are usually unavailable from stock and if ordered have to await a new melt. Some glasses, eg. UG2 and BG37 are no longer made.

Neutral density filters

Although astronomical objects are generally very faint, sometimes it is necessary to attenuate light. The NG series of Schott filters provides a large range of attenuation and are especially useful when it is better to absorb the light rather than reflect it away. However, the attenuation is not especially constant with wavelength and the glasses absorb shortward of 400nm. For astronomical objects therefore it is usually preferable to use filters made from fused silica that have been coated with a metallic alloy. This provides excellent attenuation, that although not identical for all wavelengths, is usually close enough to be easily calibrated. These coated fused silica filters can be used from the UV to 2 microns. For IR wavelengths germanium substrates are used. These filters are also made with a wedge or radial gradient of attenuation that is useful in non-quantitative situations.

Interference Filters

Thin film coating technology has matured and excellent interference filters are available from many manufacturers using computer designed coatings and computer controlled coating plants.

Bandpass filters

Bandpass interference filters are made by coating a glass or fused silica substrate with alternating layers of $\lambda/4$ reflective and $\lambda/2$ transmitting dielectric materials to make a single or multiple Fabry Perot interferometer. The spacings between the layers is designed to enhance the transmittance at the wavelength of interest. By varying the reflectivities, the number of layers and the number of Fabry-Perot cavities the shape and width of the bandpass can be altered.

The more cavities, the squarer the bandpass is. Square bandpasses are desirable for emission line photometry so that the response is uniform across the field (changing angle) and for a range of radial velocities. But for some astronomical purposes, such as broad band continuum photometry, square bandpasses are not desirable as they produce too great a response difference as a particular spectral feature moves in and out of the band due to radial velocity differences or chemical and physical differences between objects. Similarly, square bandpasses can also result in big differences when a filter is replaced by another whose bandpass is not precisely the same. For that reason, combination glass filters, or glass and interference edge filters have been preferred for continuum photometry. However, rapid advances in coating technology, including rugate filter technology, now enable arbitrary shaped bandpasses with high throughput to be made. It is likely that interference filters in the future will increasingly replace most colored glass filters.

Interference filters are produced as a glass sandwich, usually between two colored blocking glasses. Because of the hygroscopic nature of the coatings the edges are sealed with epoxy and encased in an aluminum cylinder. The filters are normally between 5 and 10mm thick depending on the diameter and the manufacturer.

Shifts in bandpass

The bandpass of an interference filter shifts blueward as the incident angle deviates from the normal. This can be useful as it enables a blueward tuning of the filter to be done. Typically a 5 degree tilt shifts the central wavelength of a 656 nm filter by about 0.7 nm while a 10 degree tilt shifts it by 2.7 nm. As most imaging is done with a converging beam the bandpass will broaden and shift blueward depending on the f/ratio of the telescope and position in the field. It is necessary to take this into account when designing a narrow band imaging filters.

Temperature will also shift the bandpass as the distance between the layers changes. Typical optical interference filters at room temperatures show shifts of about 0.003% of the peak wavelength per C. This is about 10 times less than a typical glass edge filter, such as GG395 or OG590.

Edge filters

Unlike bandpass filters, edge filters do not contain cavities. Generally they consist of quarter wave and modified quarter wave layers that produce an 'edge' in wavelength space as the filter changes from reflection to transmission. Fig. 2 shows examples of typical short pass and long pass filters. Short pass edge filters are often used with long pass glass filters to define astronomical photometric bandpasses. *Dichroic mirrors* are edge filters used at an angle of 45 degrees. In optical spectroscopy they are normally used to reflect light blueward of some limit into one spectrograph and transmit the remainder into another. They are often also used to reflect IR light to an IR instrument and transmit the optical light to a guider.

Fabry-Perot tunable filters

A FP interferometer has been introduced at two observatories that has revolutionized the way in which high efficiency intermediate to narrowband imaging can be carried out. Advances in coating techniques, precise spacing control of the interferometer plates and an innovative charge shuffling technique on the CCD detector have made this possible. More details can be found at (http://www.aao.gov.au/local/www/jbh/ttf/). The filter can be tuned between 370 and 1000 nm and the resolution chosen between 100 and 1000. At low resolutions (below 300), normal broad band BVRI filters can be used to block sidebands. At high resolution (1000) a set of intermediate interference filters are needed for sideband suppression. Unprecedented observations have been made with this new instrument.

Rugate filters

A rugate filter is an interference coating in which the refractive index of the coating varies continuously through its thickness. This provides greatly enhanced flexibility in filter design and extremely high levels of rejection. Multiple passbands can be produced, for instance to transmit two emission lines of interest, or to reject certain wavelengths, such as the strongest night sky emission lines or intense laser lines for safety goggles.

Anti-reflection coatings

Typical glass surfaces reflect about 4% of the normally incident visible and near IR light. Silicon and germanium reflect over 60%. To avoid light loss and problems associated with reflected stray light from bright stars and the sky, anti-reflection coatings are usually applied to all optics including the filters. Multilayer coatings can be designed to produce extremely low reflectivities over a wide wavelength range but for filters, a single layer coating designed for the central wavelength of the filter is usually adequate. The most effective single layer is a $\lambda/4$ thickness of material whose refractive index is the square root of that of the glass.

Bibliography

Information on glass filters can be obtained from Schott Filter Glasses (Schott: Jena Glaswerk Schott & Gen., Mainz); on optical interference filters from the Oriel Corporation (http://www.oriel.com), Melles Griot (http://www.mellesgriot.com) and Barr Associates (http://barrassociates.com) also for rugate filters; for infrared filters (http://barr-associates-uk.com).

Figure captions

Fig. 1. The transmittances of a sample of colored glass filters. The thick curves are for the ionic colored glasses UG1 (dots) and BG12. The medium thick curves with symbols are S8612 and KG3 used as red cutoff glasses. The thin curves are three of the family of shortwave cutoff glasses GG495, OG570 and RG9. msb-filter1.eps

Fig 2. The transmittances of typical multilayer (interference) edge filters. The thin curve is for short pass filter used for defining the red edge of a passband or as a heat reflecting dichroic filter. The thicker line is for a long pass filter that could be used as a dichroic beamsplitter in a spectrograph, reflecting blue light and transmitting red light. msb-filter2.eps

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